

## Article

# System Dynamics versus Agent-Based Modeling: A Review of Complexity Simulation in Construction Waste Management

Zhikun Ding, Wenyan Gong, Shenghan Li and Zezhou Wu \*

Department of Construction Management and Real Estate, College of Civil Engineering, Shenzhen University, Shenzhen 518060, China; ddzk@szu.edu.cn (Z.D.); gwy920230@163.com (W.G.); shenghan@szu.edu.cn (S.L.)

\* Correspondence: wuzezhou@szu.edu.cn; Tel.: +86-755-2653-4286

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**Abstract:** The environmental impacts caused by construction waste have attracted increasing attention in recent years. The effective management of construction waste is essential in order to reduce negative environmental influences. Construction waste management (CWM) can be viewed as a complex adaptive system, as it involves not only various factors (e.g., social, economic, and environmental), but also different stakeholders (such as developers, contractors, designers, and governmental departments) simultaneously. System dynamics (SD) and agent-based modeling (ABM) are the two most popular approaches to deal with the complexity in CWM systems. However, the two approaches have their own advantages and drawbacks. The aim of this research is to conduct a comprehensive review and develop a novel model for combining the advantages of both SD and ABM. The research findings revealed that two options can be considered when combining SD with ABM; the two options are discussed.

**Keywords:** construction waste management; system dynamics; agent-based modeling

## 1. Introduction

With the fast urbanization and rapid growth of construction activities, the amount of construction waste has been increasing significantly in past years [1–3]. In the United States, the generation of construction debris was 530 million tons in 2013; cement concrete and asphalt concrete constituted the top two components [4]. In the European Union (EU), it was reported that construction waste represents approximately 25–30% of all EU waste; however, the recycling rate was very low [5]. In Hong Kong, the generation of construction waste also took a great proportion of total solid waste, representing about one third in 2014 and 2015, respectively [6]. It also encouraged the environmentally sound management of construction waste in China [2,7,8]. From the above statistics, it can be seen that there is an urgent need for effective construction waste management. So far, relevant waste management policies and strategies have been investigated, such as waste effective design [9], on-site sorting [10], barcode system [11], low waste technology [12], prefabrication [13,14], lean management [15], building information modeling [16], etc.

The implementation of construction projects involves complexity and dynamics. Alvanchi, et al. [17] claimed that the modeling of construction systems aims to improve construction work performance by tracking the dynamic behavior of construction systems. From a systematics perspective, construction waste management (CWM) can be viewed as a complex adaptive system (CAS). A CAS is defined as “a system in which a perfect understanding of the individual parts does not automatically convey a perfect understanding of the whole system’s behavior” [18]. It is a collection of individual agents that are free to act in ways that are not totally predictable [19]. However, the actions of agents are

interconnected, which makes it is possible to learn from experiences and adapt to changes according to the external environment [20].

As CWM involves not only various factors (e.g., social, economic, environmental) but also different stakeholders (such as developers, contractors, designers, and governmental departments) simultaneously; thus, bearing the philosophy of complexity to investigate the routes of achieving effective CWM has great research potential. Scholars have investigated the adaptive characteristics of CWM systems in the literature. For example, Yuan and Wang [21] employed dynamic modeling to investigate the economic effectiveness of CWM. Ding, et al. [22] simulated the environmental performance of construction waste reduction management in China. Au, et al. [23] analyzed the impacts of government charges on the disposal of construction waste.

System dynamics (SD) and agent-based modeling (ABM) are the two most commonly used approaches for investigating the complexity in CWM. Each approach has its particular advantages and drawbacks. For example, the method of SD, as a top–down approach, allows for convenient model construction and validation. On the contrary, ABM, as a bottom–up approach, allows for sophisticated interactions between agents and heterogenous state space [24]. Currently, the existing CWM studies were conducted independently without combining the advantages of the two approaches. However, the two approaches have great potential for combining with each other so as to be more powerful. The aim of this research is to thoroughly investigate the applications of SD and ABM in CWM studies, and to discuss the potential of combining the advantages of SD and ABM in order to comprehensively deal with CWM complexities. The rest of this paper is organized as follows. Firstly, the SD and ABM approaches are introduced in Section 2. Then, the applications of these two approaches in CWM studies are reviewed and presented in Section 3. Subsequently, a comparison of the two approaches is made, and discussions of the combination are made in Section 4. Finally, conclusions are given in Section 5.

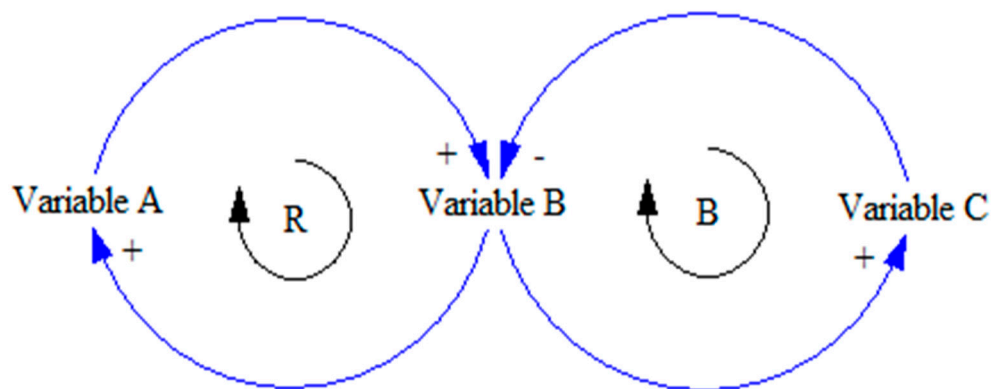
## 2. Overview of System Dynamics (SD) and Agent-Based Modeling (ABM)

Complexity science has attracted substantial attention from scholars in various disciplines, ranging from physics, economics, and computer science to social science [25–27]. It deals with the nonlinear relationships in a complex system, focusing on the characteristics and interaction rules among the components. To explore the complexity in a complex system, system dynamics (SD) and agent-based modeling (ABM) are the two most commonly used approaches.

### 2.1. System Dynamics (SD)

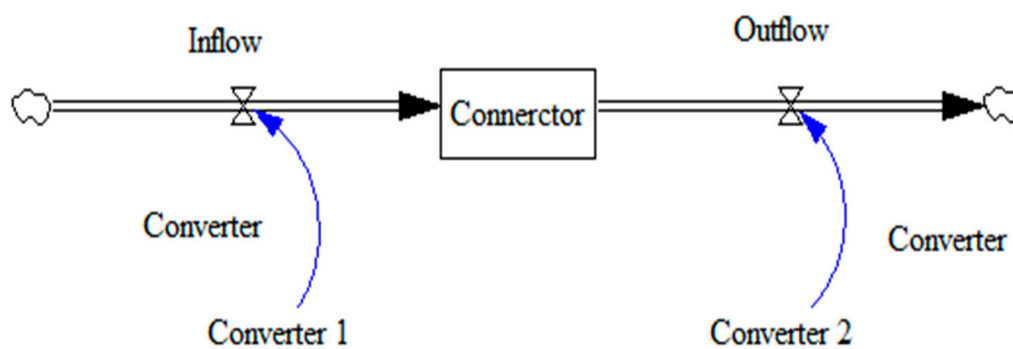
System Dynamics (SD) is a top–down information feedback method that was proposed by Professor Forrester [28]. The essence of this method is the feedback structures with high order, multiloop, and nonlinearity. SD is a well-developed approach for visualizing, analyzing, and understanding complex dynamic feedbacks [29].

Diagramming tools, such as causal loop diagrams (CLDs) and stock–flow diagrams (SFDs), are used to capture the structure of a complex system [30]. CLDs are able to map the feedback structures of a complex system; they can show how the system is dynamically influenced by the interactions of all of the variables. A CLD consists of variables connected by arrows; the arrows denote the causal influences among the variables. Each causal link is assigned a polarity—either positive (+) or negative (–)—to indicate how the dependent variables are influenced by the independent variables. The important loops are highlighted by a loop identifier, showing whether the loops are positive (reinforcing) or negative (balancing). An illustrative CLD is presented in Figure 1. A positive feedback illustrates that a change in any of the variables within the causal loop will eventually affect itself in a positive way, while a negative feedback means that a change on any variables within the causal loop will affect itself in a negative way [22].



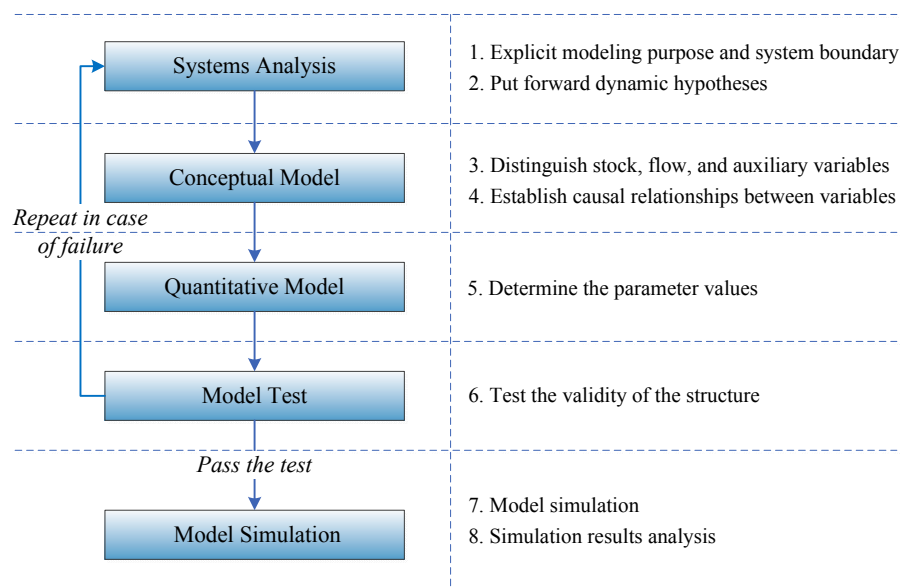
**Figure 1.** An illustrative causal loop diagram (CLD).

The CLDs can successfully describe the basic logical structures; however, in order to conduct a quantitative analysis, SFDs should be employed. SFDs can distinguish the nature of different variables and use integral or differential equations to represent the described information. Four building blocks are used to develop a quantitative SFD from a qualitative CLD: stock, flow, converter, and connector [31], as shown in Figure 2. Stocks create delays by accumulating the difference between the inflow and the outflow. By decoupling the rates of flows, stocks are the source of disequilibrium dynamics. Flows are the functions of the stock and other state variables and parameters [30]. The value of a flow can be positive or negative. A positive flow is an inflow that will fill in the stock, while a negative flow is an outflow draining from the stock. A converter has a utilitarian role in selecting the proper values and functions of the parameters in the model, and a connector is an information transmitter connecting elements [32].



**Figure 2.** An illustrative stock–flow diagram (SFD).

A flow chart of the model development and simulation process is presented in Figure 3. From this figure, it can be seen that the basic procedure of an SD modeling covers the system analysis stage, the establishment of the conceptual model stage, the establishment of the quantitative model stage, the model verification stage, and the model simulation stage.

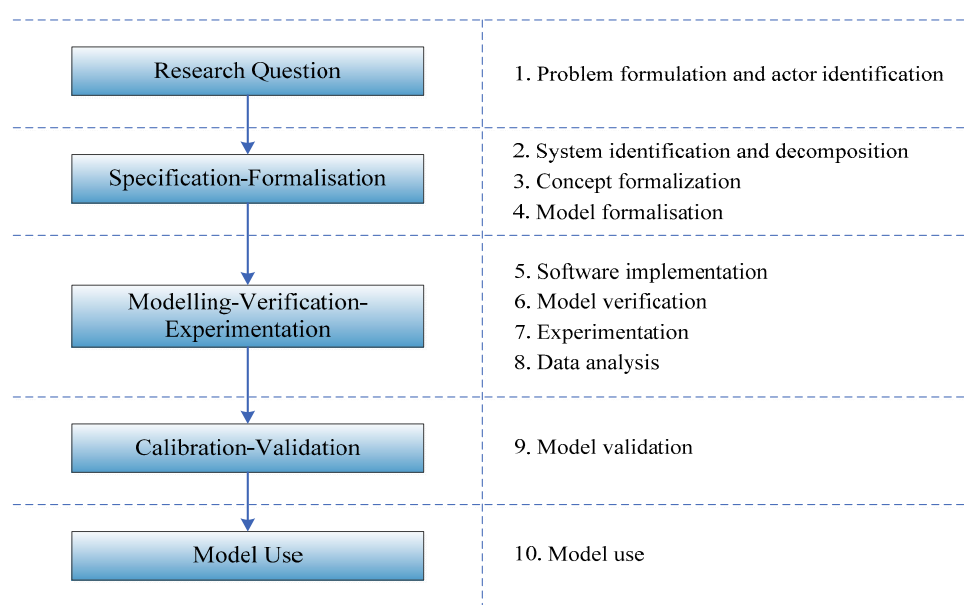


**Figure 3.** A flow chart of system dynamics (SD) modeling.

## 2.2. Agent-Based Modeling (ABM)

In contrary to SD, agent-based modeling (ABM) is a bottom-up computational modeling approach. By using ABM, the individual entities in a CAS are represented by discrete agents that interact autonomously in a simulated space to produce emergent and non-intuitive outcomes at the population level [33]. The interactions or communications among the agents are made according to a set of predefined “rules” [34]. The rules governing individual agents’ behavior are influential to the outcomes/predictions of ABM; thus, it is necessary to tightly couple all of the rule-based algorithms at all of the stages of model development.

ABM can be implemented by programming languages (e.g., C, Java, and Python) or specialized toolkits such as NetLogo, Swarm, and Repast. Generally, ABM follows an incremental modeling process by starting from a simple model to a complex model [35]. This process is illustrated in Figure 4.



**Figure 4.** The process of agent-based modeling (ABM).

### 3. The Application of SD and ABM in CWM Studies

Both SD and ABM have been used successfully to explore and understand CASs in different disciplines [36]. The applications of SD and ABM in CWM studies are presented as follows.

#### 3.1. The Application of SD in CWM Research

A CWM system involves various aspects: waste generation, reduction, reuse, recycling, transportation, etc. Several factors can affect the process of CWM, such as environment-related factors, economic-related factors, social-related factors, etc. There are interactions among these factors; thus, it is necessary to select an appropriate technique to simulate the complex relationships. SD can be used to investigate CWM systems, because it could not only precisely describe the cause–effect relationships among the quantitative variables, it could also properly define qualitative variables. A summary of SD application in CWM studies is shown in Table 1. From Table 1, it can be seen that the previous studies mainly focused on the general aspects of CWM, such as policy, the environment, the economy, society, and construction waste management issues. In terms of modeling software, iThink, Vensim, and Stella are the most popular.

**Table 1.** Construction waste management (CWM)-related studies based on system dynamics (SD).

Topic	Selected Paper	Software	Main Focus
Policy	[37]	Vensim	Develop an SD-based model to determine an optimal charging system that could reduce construction waste generation and maximize waste recycling.
	[38]	Vensim	Assess the effectiveness of two policies (i.e., incentives and tax penalties) to evaluate how the government can influence the behavior of firms in terms of construction waste recycling.
	[39]	Vensim	Evaluate the possible impacts arising from the application of prefabrication on construction waste reduction.
Environment	[40]	iThink	Develop an SD-based model for evaluating the environmental performance of CWM.
	[22]	Vensim	Simulate the environmental performance of construction waste reduction management.
Society	[41]	iThink	Develop an SD-based model for quantitatively evaluating the social performance of CWM to provide insights for an effective promotion.
Economy	[42]	iThink	Highlight the dynamics and interrelationships of CWM practices and analyze the cost–benefit of this process.
	[21]	Vensim	Investigate the economic effectiveness of CWM and provide insightful recommendations for decision making.
	[43]	iThink	Analyze the cost and benefit of CWM from the standpoint of the contractor, and simulate the effects of economic compensations and penalties.
Policy–economy	[44]	Vensim	Evaluate alternative types of recycling centers under different policy and economy scenarios.
Environment–economy	[45]	Stella	Evaluate the impacts of two alternatives (i.e., recycling and disposing) for CWM.
Management	[46]	Stella	Develop an SD-based model by incorporating the relationships of major activities to assist practitioners in better understanding the complexity of CDW.
	[47]	iThink	Develop a simulation model that can better reveal the interrelationships of factors during the on-site waste sorting process.
	[48]	Stella	Develop a model of on-site construction waste management. The interconnections of the main activities are included in the model, with a focus on planning and management.
	[49]	iThink	Develop a simulation model integrating four sub-systems including construction waste generation, on-site waste sorting, waste landfill, and public filling.
	[50]	iThink	Propose a model that can serve as a decision support tool for construction waste reduction and provide a platform for simulating the effects of various reduction strategies.
	[51]	Stella	Examine the complexity of CWM by analyzing waste generation, transportation, recycling, landfilling, and illegal dumping.

Although SD has been successfully employed in CWM research, some limitations were identified during application. Generally speaking, the SD model is based on the idea that all of the dynamics occur due to the accumulation of flows in stocks. Through a literature review, it was found that SD models did not provide an appropriate means to depict individual differences (e.g., various waste management participants' preferences and waste collection levels). For instance, the SD model established by Yuan, et al. [42] only showed that the environmental awareness had an influence on waste generation and recycling. In other words, it was assumed that the interaction differences between related stakeholders (e.g., contractors, governments, designers) and the information distribution among them are homogeneous. However, in reality, the environmental awareness of different stakeholders is different; the environmental awareness among stakeholders may interact with each other. Thus, SD has a drawback that cannot provide full interpretations of how the microscopic stakeholders' behavior would affect the emergent macro phenomena. It is necessary to explore a solution to investigate CWM more comprehensively.

### 3.2. The Application of ABM in CWM Research

A CWM system involves various stakeholders, such as contractors, developers, transportation companies, recycling/landfilling centers, government departments, etc. These stakeholders are adaptable to the environment; they can communicate with the environment to change their behavior through continuous learning and the accumulation of experience. Hence, a bottom-up ABM method is capable of bridging the gap between microscopic behavior and macro phenomena in a CWM system [52].

Previous research using ABM primarily focused on the treatment alternatives of construction waste. Based on empirical data, Knoeri, et al. [53] presented an ABM of the Swiss recycled construction material market. It was found that raising construction stakeholders' awareness of recycled materials in combination with small price incentives was most effective for promoting the use of recycled materials. Gan and Cheng [54] employed ABM to analyze the dynamic network of a backfill supply chain so as to maximize the backfill recovery and reduce the amount of construction waste to landfills. Ding, et al. [55] developed an ABM for simulating CWM measures to reveal interactions between the primary stakeholders and impacts on the environment. The construction waste generation and effects of various policies were investigated. In terms of the waste generated from demolition activities, Ding, et al. [56] compared the differences of environmental impacts between green demolition and traditional dismantling using the ABM method.

From the above research, it can be concluded that ABM is more applicable to simulate a dynamic system due to its decentralization and fast reaction to unexpected disturbances. ABM has the advantage of direct one-to-one mapping between real and virtual agents in terms of parameter acquisition from experiments and model validation. In a CWM simulation model, agents are divided according to CWM stakeholders, such as construction enterprises, demolition companies, and transportation companies. Each agent has its own states, attributes, and behavior, allowing ABM to investigate system complexity and interactions from a lower individual agent level to emergent results at a higher level [57]. ABM generally focuses on micro-level interactions that may explain emergent patterns such as waste environmental performance at a system level. However, it ignores the feedback effect of various social and economic factors on the individuals. For example, in the ABM developed by Ding, et al. [55], the interactions between the agents and the economic and social environment were not considered.

## 4. Discussion

From the above literature review, it can be seen that both SD and ABM have been successfully applied to investigate CWM-related studies. However, there are drawbacks for each approach. It is worthwhile to explore the possibility of combining the advantages of the two approaches.



#### 4.1. Comparison of SD and ABM

Both SD and ABM can explore complexity problems in a CAS; however, there are differences between the two approaches:

- SD is usually used to analyze problems from a macro and holistic-thinking perspective. It is a “top–down” modeling approach that can avoid the limitations of one-sided thinking (e.g., the micro perspective) and help understand the structure behind a complex phenomenon [58]. An SD model can be used to study a dynamic evolution process under different situations. The philosophical foundation is reductionism. Reductionism is a process of breaking complex entities, concepts, or phenomena down into their smallest constituents; it can transform ideas into simple forms [59]. However, SD is often criticized, because a complex system cannot be fully understood by just dealing with a single discipline. In terms of the CWM system, SD cannot give a profound explanation of the micro behaviors in the system, because it ignores the relationship between the macro behavior and micro behavior.
- ABM provides a dynamic approach by building a virtual system. It follows a “bottom–up” procedure that emphasizes the spatial or social interactions between individuals and their environment [60]. The philosophical foundation is syncretism. The importance of holistic analysis is emphasized; meanwhile, the composing parts are also involved [61]. ABM is an effective cross-scale modeling method that combines time dimension with space dimension, and bears the characteristics of heterogeneity, space discretization, time discretization, and discrete states [60]. Through computer simulation, the microscopic mechanism of complex macro phenomena can be revealed. However, Wang and Deisboeck [62] claimed that ABM also has some weaknesses. Firstly, it is too detailed to simulate over a long period because of the large number of parameters and rules, which makes parameter identification difficult and requires extensive sensitivity analyses to determine the prediction robustness. Secondly, ABM is sensitive to small variations; thus, current ABM can only process a relatively small number of agents. Thirdly, ABM ignores the interactions between agents and macro factors.

In summary, SD and ABM have their own advantages and disadvantages for analyzing complex systems. SD focuses on the “flow” relationships and feedbacks that can longitudinally simulate a system’s dynamic behavior. It is appropriate to analyze the interactions between different elements and cumulative longitudinal effects. However, spatial factors are not covered in the SD modeling process. In contrast, ABM considers the spatial interactions. However, the feedback effect of various social and economic factors on agents is ignored. A more detailed comparison is presented in Figure 5.

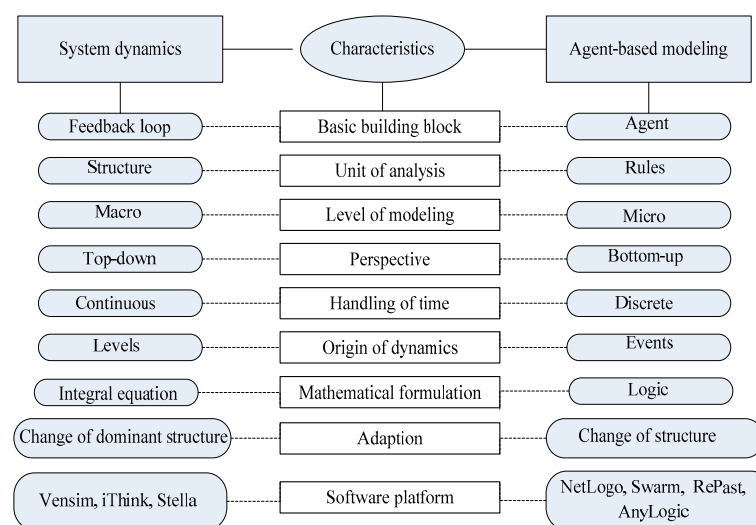


Figure 5. Comparison between SD and ABM.

#### 4.2. Combination of SD and ABM for CWM Research

Considering the advantages and drawbacks of SD and ABM, a combination of the two approaches is essential in order to overcome their limitations:

- (1) SD models cannot consider different levels of aggregation; however, ABM has the ability to capture a fine level of detail. Thus, SD can have the highest abstraction level, and ABM can be used at lower abstraction levels, varying the nature and scale of elements [63,64].
- (2) SD ignores the effects of heterogeneous mixing; each stock consists of homogeneous elements. Thus, distinctions within the elements (i.e., heterogeneities of any kind) have to be modeled by adding new stocks. However, the heterogeneous agents can be easily established by using ABM [65].
- (3) SD is equation-based, and needs quantified relationships between variables; thus, it is not suitable for complex systems with unknown structures. However, ABM can reasonably represent complex systems based on a limited number of relatively simple rules to reveal emergent behavior [36].

The combination of SD and ABM has been attempted in other disciplines. For instance, Größler, et al. [66] presented a software-based integration of SD and ABM that investigated supply chain management. The results showed that Vensim and RePast can be used simultaneously to solve the technical problem of combining the two methods. In the same vein, it is feasible to integrate SD and ABM to solve complexity problems in the CWM field.

There are two options to integrate SD and ABM, as shown in Figure 6. The first option is the ABM method, which is based on SD. This option models a certain number of objects on the macro level (SD part), inside which agents are modeled at the micro level (ABM part). An illustration of the ABM method based on SD for CWM is presented in Figure 7. The other option is the SD method based on ABM. It models interactions of agents at the macro level (ABM part), and their internal structure at the micro level (SD part). An example of the SD method based on ABM is given, as shown in Figure 8.

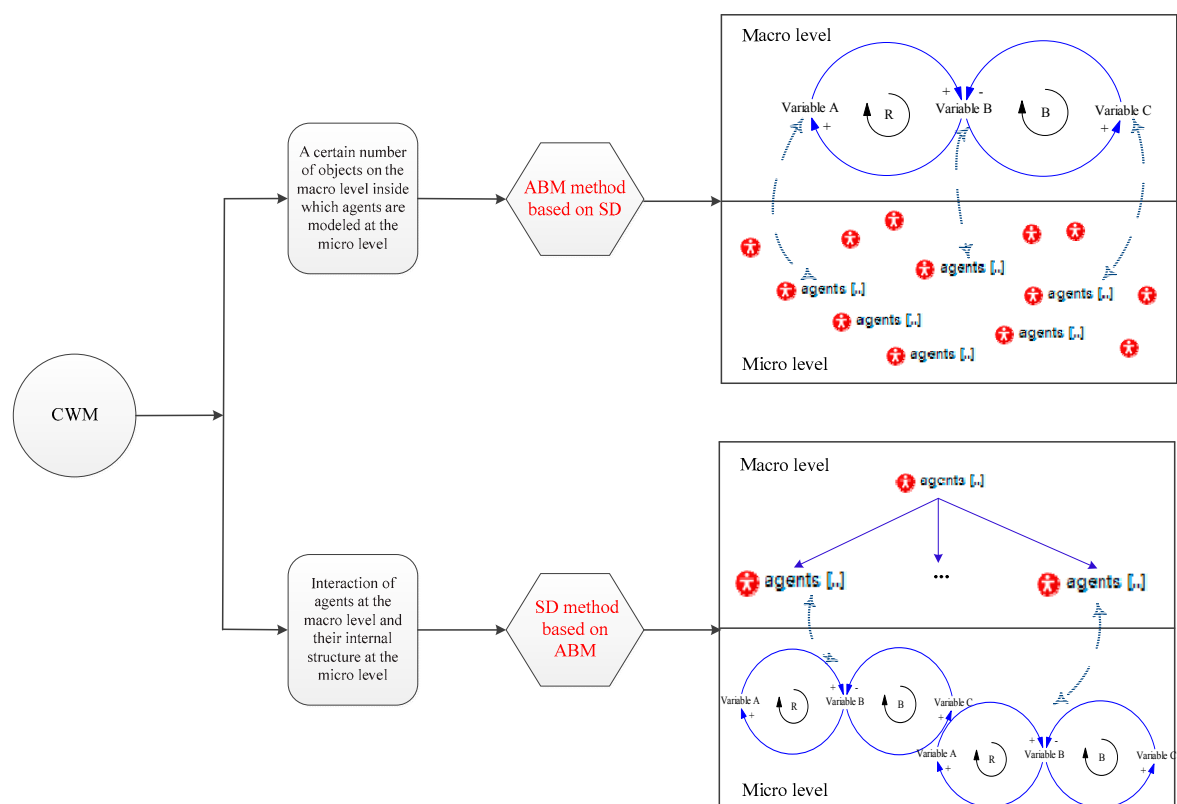


Figure 6. Two options for combining SD and ABM.



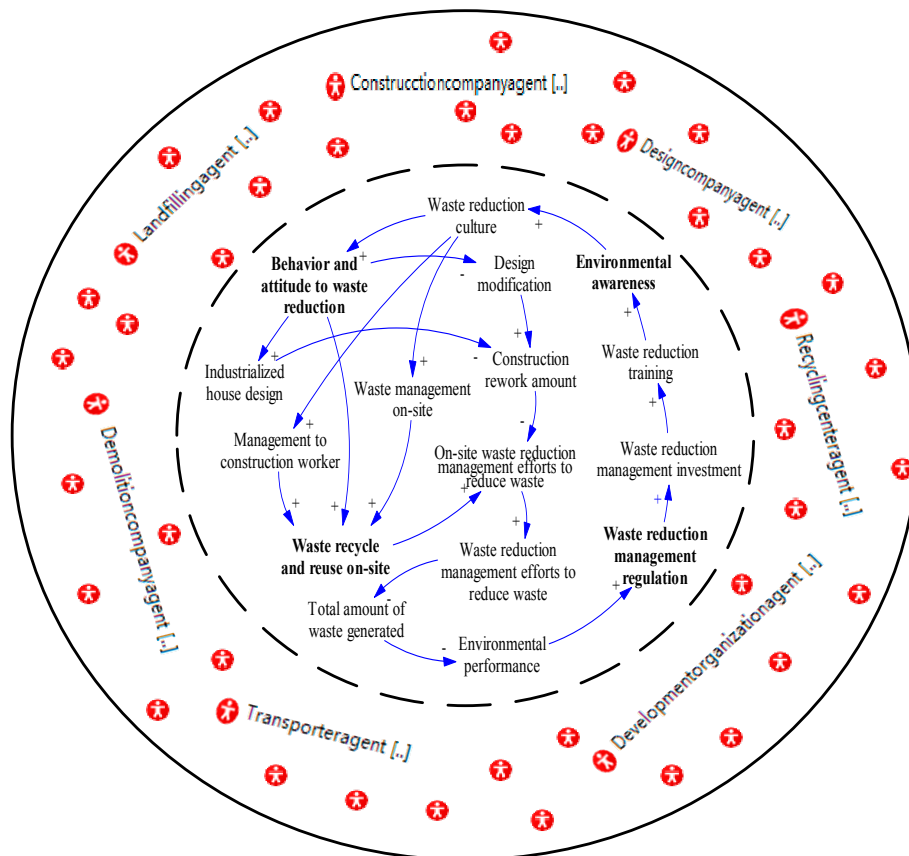


Figure 7. ABM method based on SD.

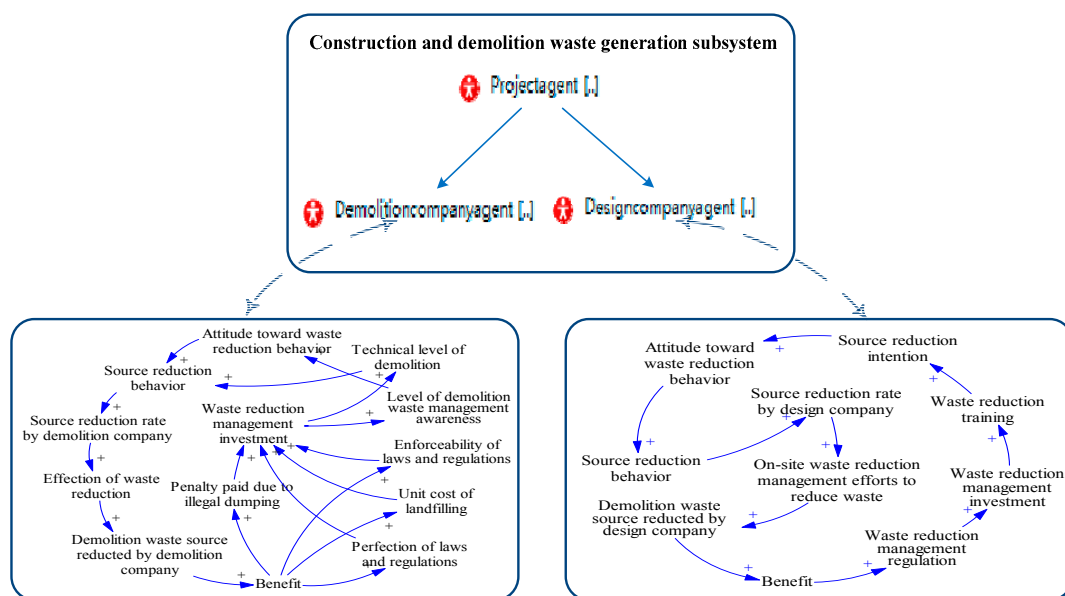


Figure 8. SD method based on ABM.

## 5. Conclusions

Construction waste has great negative impacts on the environment. Recently, researchers and practitioners have paid attention to the effective management of construction waste. Construction waste management (CWM) is a complex adaptive system that involves not only various factors (e.g.,

social, economic, and environmental) but also different stakeholders (such as developers, contractors, designers, and governmental departments) simultaneously. Thus, it is necessary to investigate the complexity of CWM based on complexity theories.

This paper reviewed the SD and ABM applications in the field of CWM. The findings revealed that the economic, social, and environmental aspects of CWM have been investigated. SD and ABM are totally different from each other: SD is a top–down modeling method that describes systems from a macro perspective, requiring knowledge of the system relations and causalities. ABM, on the contrary, is a bottom–up approach that models single acting entities of the system and the agents’ interactions during simulation in order to determine the macro behavior of a system.

Both SD and ABM approaches have their advantages and drawbacks; thus, it is necessary to combine the two approaches in order to achieve a more powerful approach. Two options are proposed in this study for potential combination: namely, an ABM method based on SD, and an SD method based on ABM. Based on the proposed combinations, further studies can be conducted to comprehensively investigate the complexity in CWM-related systems.

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